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DERIVED SURFACE CONTAMINATION LIMITS FOR THE URANIUM MINING AND MILLING INDUSTRY

by

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ABSTRACT

Derived Surface Contamination Limits (DSCL) are proposed for the control of surface contamination at the work place for the uranium mining and milling industry. They have been derived by a method incorporating recent ICRP recommendations and consideration of the radiation exposure pathways of ingestion, inhalation and external irradiation of the basal layer of skin.

It is shown that for simplicity of monitoring these DSCLs can usually be expressed in terms of beta activity instead of alpha activity, because for most contaminants the ratio of beta to alpha activities are well known.

A generalized DSCL of 10^5 Bq/m^2 of beta activity is recommended for all contaminants likely to be found in uranium mine and mill workplaces except for fresh uranium concentrates. In the latter case, the DSCL is expressed in terms of alpha activity because the ratio of beta to alpha activities for fresh uranium concentrates is variable; the beta activity increases with the ingrowth of U-238 daughter products (Th-234 and Pa-234m) until secular equilibrium is re-established in about six months. Contamination of the order of the limiting value will be clearly visible on a contrasting surface and compliance with the DSCL would be a simple matter of removing all visible uranium concentrate from the surface.

A surface contamination limit of 10^4 Bq/m^2 of beta activity is proposed for the release of non-porous materials and equipment with no detectable loose contamination to the public domain.

RÉSUMÉ

Le présent rapport propose des limites dérivées de contamination de surface (LDCS) pour le contrôle de la contamination des surfaces des lieux de travail dans les mines et usines de concentration d'uranium. On a dérivé ces limites à partir d'une méthode qui incorpore des recommandations récentes de la CIPR et en tenant compte de certaines voies d'acheminement des rayonnements, soit l'ingestion, l'inhalation et l'irradiation externe de la couche basale de la peau.

On démontre que ces LDCS peuvent être presque toujours exprimées en termes d'activité bêta plutôt que d'activité alpha pour simplifier la surveillance, car la proportion entre l'activité alpha et l'activité bêta est bien connue pour la plupart des contaminants.

Une LDCS générale de 10^5 Bq/m^2 d'activité bêta est recommandée pour tous les contaminants qu'on pourrait trouver dans les lieux de travail des mines et usines de concentration d'uranium, exception faite du concentré uranifère frais. La LDCS de ce dernier est plutôt exprimée en termes d'activité alpha parce que la proportion entre l'activité alpha et l'activité bêta est variable. L'activité bêta du concentré uranifère frais augmente en proportion de la production de produits de filiation d'U 238, soit le Th 234 et le Pa 234m, jusqu'à ce qu'un équilibre durable soit réétabli au bout d'environ six mois.

De toutes façons, une contamination de l'ordre de la valeur limite sera clairement visible sur une surface contrastante et il ne s'agirait simplement que d'enlever le concentré uranifère frais de cette surface pour se conformer à la LDCS.

Le rapport présente aussi une LDCS de 10^4 Bq/m^2 d'activité bêta pour le transfert dans le secteur public de matériaux non poreux et de l'équipement qui n'ont aucune contamination non fixée détectable.

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A. Introduction

Radioactive contamination on surfaces can become airborne and subsequently inhaled, it may be transferred by contact to the hands and subsequently to food and hence ingested, or it may penetrate the intact skin or enter a wound giving rise to internal contamination. In addition, beta emitters on the skin may give rise to an external radiation dose.

If a contaminated article is moved to an inactive area of a nuclear facility where the presence of radioactive materials is not expected, it might be handled without the precautions normally taken with radioactive materials. In order to limit the dose arising from contaminated surfaces, quantities known as Derived Surface Contamination Limits (DSCL) have been established. These limits will ensure that the radiation dose as a result of contamination will not exceed the dose limits prescribed in the Atomic Energy Control Regulations.

In this document, the method developed by Dunster (2) for derivation of surface contamination limits in the nuclear power generation industry, with some minor modifications, is adopted for the establishment of DSCLs for the uranium mining and milling industry. The modifications are necessary in order to reflect the 1977 recommendations of the ICRP (3, 4) which are different from those used by Dunster (2) in 1962. The recommended dose limit for the skin now is 500 mSv/year (compared to 750 mSv/year for extremities and 300 mSv for skin in general in ICRP 2 - reference 1) and the concepts of maximum permissible concentrations in air and water have been replaced by annual limits of intake (ALI). In addition, Dunster derived DSCLs for mixtures of radionuclides in the same radioactive decay chain (e.g. natural uranium and natural thorium) using the maximum permissible concentrations in air and water for mixtures provided by ICRP 2, while the ALIs for mixtures of radionuclides in the same radioactive decay chain must be derived from the method outlined in ICRP 30 before any DSCL can be calculated. The derivation of these ALIs is outlined in Appendices II and III. The ALIs for all mixtures of importance in the uranium processing industry are listed in Table I.

Similar DSCLs for the work place have also been established in other countries for the mining and milling of radioactive ores (e.g. reference 5 - 3.7×10^5 Bq m^{-2} for surfaces in controlled and supervised areas).

B. Derivation of Surface Contamination Limits for the Uranium Mining and Milling Industry

(i) Limits based on inhalation:

To estimate the amount of surface contamination which may become airborne under a variety of conditions, resuspension factors (also called dispersion constants by Dunster) defined as the ratio of the air concentration (Bq/m^3) to the surface contamination (Bq/m^2) are obtained from Reference 2. These resuspension factors range from 4×10^{-5} m^{-1} to 1×10^{-6} m^{-1}. The highest value of 4×10^{-5} m^{-1} was obtained in an enclosed and unventilated area, where the resuspension of dust resulted from digging through dusty building rubble. The author stated that for controlled areas (e.g., nuclear power reactors) a value of 2×10^{-6} m^{-1} was sufficiently conservative for long term use. H. Glauberman et al (6) also obtained resuspension factors of the same order of magnitude in their experiments on resuspension of settled particulates in a uranium processing plant with ventilation control and under simulated working conditions. A resuspension factor of 2×10^{-6} m^{-1} is used in this text.

Using the ALI for inhalation for each mixture of radionuclides (e.g., uranium ore with no thorium) from Table I, the DSCL for inhalation for each mixture can be obtained by dividing the ALI by 2.4×10^3 $m^3 a^{-1}$ (i.e. the annual air intake by a worker, ICRP 23) and the resuspension factor of 2×10^{-6} m^{-1}.

These DSCLs are listed in Table II and sample calculations are shown in Appendix IV.

(ii) Limits based on ingestion:

The most likely route for ingestion is via contaminated hands.

Few quantitative data are available for relating skin contamination levels to the rate of ingestion but Dunster assumed that a person may ingest all the contamination from 10^{-3} m^2 of skin every day (2). The DSCLs for ingestion can be obtained by dividing the ALIs for ingestion from Table I by this contaminated area of 10^{-3} m^2/day and 250 working days in a year. These DSCLs are listed in Table II, and sample calculations are outlined in Appendix IV.

(iii) Limit based on external irradiation of the skin:

The ICRP recommended occupational dose limit of 500 mSv for skin is based on non-stochastic effect of radiation.

The dose limit for the skin applies to the dose in the basal cell layer, and although the ICRP recognizes that the depth of the basal layer varies considerably from one part of the body to another, it recommends the use of 70 μm as a reasonable mean value for practical dose assessment (3). Hence, this value is used in this report.

The maximum energy of the alpha emitters in uranium mines and mills is 4.78 MeV (excluding radon and thoron daughters) which corresponds to a maximum range of about 3 mg cm^{-2} in the skin, and therefore the dose to the basal cell layer from alpha emitters on the skin is zero. Calculations similar to those outlined in reference (7) indicate that the dose to the basal cell layer of the skin from gamma radiation is negligible compared to the dose from beta radiation. Beta radiation is therefore the main source of external radiation from surfaces contaminated with uranium and thorium and their decay products.

The dose rate to the basal cell layer from contact with a planar source of beta particles having maximum energy in the range of 0.5 to 3.0 MeV is about 0.2 nGy/h per Bq/m^2 (derived from reference 8). The dose limit for the skin is 500 mSv/year. Therefore, for 2,000 working hours per year, the DSCL for beta emitting contamination would be 10^6 Bq/m^2.

C. Discussion and Conclusions

(i) As indicated in Table II, inhalation is generally the limiting pathway for occupational intake of mixtures of importance in the uranium mining and milling industry.

The most restrictive ALI for the inhalation pathway for the mixtures considered is 10^5 Bq/m^2, which is the ALI for uranium ore with a 4:1 Th-232 to U-238 ratio (4:1 being the highest ratio of Th-232 to U-238 in existing Canadian ore, Appendix III).

(ii) It follows from the above that the most restrictive DSCL derived from the inhalation pathway will be appropriate for surface contamination control. However, there is a problem in monitoring because this DSCL is derived from the ALIs for a mixture of beta and alpha emitters. Fortunately, the matter is simplified in the uranium processing industry because for each mixture there is a known ratio between the activities of beta and alpha emitters. For finely divided uranium ore, the ratio is always 4:5 if it is assumed that the radon gas emanates from the ore particles immediately after it is produced.

(iii) Current technology extracts most of the uranium but only a comparatively small fraction of the other radionuclides in the ore. Hence, the tailings contain approximately the same concentrations of other radionuclides as the original ore minus the uranium (9). The ratio of beta to alpha activities in this case is 4:3.

(iv) The activity ratio between beta emitters and alpha emitters for uranium concentrate (yellowcake) is 1:1 after equilibrium between U-238, Th-234, Pa-234m and U-234 is re-established (approximately 6 months after processing).

(v) The DSCLs can be expressed as either beta or alpha activities. For example, the DSCL for the inhalation pathway for uranium ore with no thorium is 6.0×10^5 Bq/m^2 of total alpha and beta activities at a fixed ratio of 4:5 for beta/alpha. Rounding to the first significant figure, as are the ALIs in ICRP 30, the DSCL can be expressed as either 3×10^5 Bq of beta/m^2 or 3×10^5 Bq of alpha/m^2. It is usually more convenient to monitor for beta than alpha radiation in work places.

D. Recommendations

(i) Recommended DSCLs for each mixture are shown in Table III.

The value of 1×10^5 Bq/m^2 for unidentified beta or alpha activities is included to account for mixtures in which the nature of the mixture is unknown or too difficult to identify.

(ii) It would be more convenient to monitor these DSCLs in terms of beta activity except for the special case of fresh uranium concentrates where little or no beta activity is present.

In the case of fresh uranium concentrates (yellowcake) the DSCL has to be expressed in terms of alpha activity. In practice this may not be a difficulty since for a surface with a contamination level of 3×10^5 Bq/m^2 of uranium concentrates, there would be about 15 grams of uranium concentrate per square metre (see Appendix V). This amount is quite visible against a contrasting background, and compliance in accordance with the DSCL would be a simple matter of removing most of the loose yellowcake from the surface. A similar calculation shows that there can be about 3000 grams of low grade ore (0.2%U) on a surface of one square metre before the DSCL is exceeded (see Appendix VI).

E. Further Application of DSCLs

The DSCL recommended in section (D) for surface with unidentified contamination, with some modifications, may also be used as a general guide to decide whether non-porous materials and equipment having contamination only on exterior surfaces can be released to uncontrolled areas outside the nuclear industry. If the exterior surfaces of these materials and equipment are cleaned of any loose contamination, one tenth of this DSCL (i.e. $1/10 \times 10^5$ Bq/m^2 beta activity) is a number appropriate for general use. It is shown in appendix VII, A & B that any dose resulting from the usage of such material will be well below the dose limit for members of the public.

This surface contamination limit (10^4 Bq/m^2 of beta activity) is not applicable for porous materials because contaminants may be trapped inside the material and surface contamination monitoring cannot account for all the contaminants present.

TABLE I

Annual Limit of Intake (ALI) For Mixtures of Radionuclides (Bq)

	Pathways	
	Ingestion	Inhalation
1) Uranium Ore with no thorium:		
Beta activity	8×10^4	1.3×10^3
Alpha activity	1×10^5	1.7×10^3
2) Uranium Ore with a Th-232 to U-238 ratio of 4:1		
Beta activity	1.0×10^5	5.0×10^2
Alpha activity	1.0×10^5	7.0×10^2
3) Yellowcake (at least 6 months old)		
Beta activity	7.2×10^5	1.4×10^3
Alpha activity	7.2×10^5	1.4×10^3
4) Tailings from Ore with no thorium		
Beta activity	9.2×10^4	2.2×10^3
Alpha activity	6.9×10^4	1.6×10^3
5) Tailings from Ore with a Th:U ratio of 4:1		
Beta activity	6.6×10^4	2.2×10^2
Alpha activity	9.0×10^4	6.0×10^2
6) Fresh Yellowcake		
Beta activity	-	-
Alpha activity	7×10^5	1×10^3

TABLE II

Derived Surface Contamination Limits for Mixtures Of Importance in the Uranium Mining and Milling Industry (Bq/m^2)

	Pathways		
	Ingestion	Inhalation	External Irradiation of skin
1) Uranium Ore with no thorium			
Beta activity	4.0×10^5	3.0×10^5	1×10^6
Alpha activity	4.0×10^5	3.0×10^5	-
2) Uranium Ore with a Th-232 to U-238 ratio of 4:1			
Beta activity	3.0×10^5	1.0×10^5	1×10^6
Alpha activity	5.0×10^5	2.0×10^5	-
3) Yellowcake (6 months old)			
Beta activity	3.0×10^6	3.0×10^5	1×10^6
Alpha activity	3.0×10^6	3.0×10^5	-
4) Tailings from Ore with no Thorium			
Beta activity	4.0×10^5	4.0×10^5	1×10^6
Alpha activity	3.0×10^5	3.0×10^5	-
5) Tailings from Ore with a Th-232 to U-238 ratio of 4:1			
Beta activity	4.0×10^5	1.0×10^5	1×10^6
Alpha activity	4.0×10^5	1.0×10^5	-
6) Fresh Yellowcake			
Beta activity	-	-	-
Alpha activity	3×10^6	3×10^5	-

TABLE III

Recommended Derived Surface Contamination Limits For Different Mixtures At The Work Place

Mixture	DSCLs (Bq/m^2) Beta	Alpha
1) Uranium Ore with no Thorium	2×10^5	4×10^5
2) Uranium Ore with a Th-232 to U-238 ratio of 4:1	1×10^5	2×10^5
3) Yellowcake	3×10^5	3×10^5
4) Tailings from Ore with no Thorium	4×10^5	3×10^5
5) Tailings from Ore with a Th-232 to U-238 ratio of 4:1	1×10^5	1×10^5
6) Fresh Yellowcake	-	3×10^5
7) Unidentified Contamination	1×10^5	1×10^5

TABLE IV

Recommended Derived Surface Contamination Limits For Release of Slightly Contaminated Materials for Use Outside the Nuclear Industry

Condition	Limit (Beta) in Bq/m^2
Surfaces must be cleaned and stripped of any loose contaminants	1×10^4

References

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APPENDIX I

ALIs and DACs for Most of the Radionuclides in the U-238, U-235 and Th-232 Decay Chains

Radionuclide		Pathways: Ingestion	Pathways: Inhalation	(Class)*
a) U-238 Chain:				
U-238	ALI	8×10^5	2×10^3	(Y)
	DAC	-	7×10^{-1}	
Th-234	ALI	1×10^7	6×10^6	(Y)
	DAC	-	2×10^3	
Pa-234m	ALI	9×10^7	2×10^8	(Y)
	DAC	-	1×10^5	
U-234	ALI	7×10^5	1×10^3	(Y)
	DAC	-	6×10^{-1}	
Th-230	ALI	4×10^5	7×10^2	(W)
	DAC	-	2.0×10^{-1}	
Ra-226	ALI	2×10^5	2×10^4	(W)
	DAC	-	1×10^1	
Pb-210	ALI	4×10^4	1×10^4	(W)
	DAC	-	4×10^0	
Bi-210	ALI	3×10^7	1×10^6	(W)
	DAC	-	4×10^2	
Po-210	ALI	1×10^5	2×10^4	(W)
	DAC	-	1×10^1	

* The most restrictive class is assumed.
ALI Bqa^{-1}
DAC Bq/m^3

To describe the clearance of inhaled radioactive materials from the lung, materials are classified as D, W, or Y which refer to their retention in the pulmonary region. This classification applies to a range of half-times for D of less than 10 days, for W from 10 to 100 days and for Y greater than 100 days.

APPENDIX I (CONT'D)

b) Th-232 Chain

Th-232	ALI	7×10^{3}	2×10^{3}	(Y)
	DAC	-	8×10^{-2}	
Ra-228	ALI	1×10^{5}	4×10^{4}	(Y)
	DAC	-	2×10^{1}	
AC-228	ALI	9×10^{7}	2×10^{6}	(Y)
	DAC	-	8×10^{2}	
Th-228	ALI	5×10^{5}	6×10^{2}	(Y)
	DAC	-	3×10^{-1}	
Ra-224	ALI	6×10^{5}	6×10^{4}	(W)
	DAC	-	3×10^{1}	

C) U-235 Chain

U-235	ALI	7×10^{5}	2×10^{3}	(W)
	DAC	-	6×10^{-1}	
Th-231	ALI	1×10^{8}	2×10^{8}	(W)
	DAC	-	1×10^{5}	
Pa-231	ALI	1×10^{3}	9×10^{1}	(W)
	DAC	-	5×10^{2}	
AC-227	ALI	1×10^{5}	2×10^{2}	(W)
	DAC	-	1×10^{1}	
Th-227	ALI	5×10^{6}	1×10^{4}	(W)
	DAC	-	5×10^{0}	
Ra-223	ALI	3×10^{5}	3×10^{4}	(Y)
	DAC	-	1×10^{1}	

APPENDIX II

Annual Limits of Intake for Uranium Ore

The ALI for a mixture of radionuclides consisting of activities a, b, ... x, is set such that:

$$\frac{Ia}{ALI_a} + \frac{Ib}{ALI_b} + \ldots + \frac{Ix}{ALI_x} = 1 \qquad \text{.....Equation (1)}$$

where, Ia is the maximum annual activity intake of radionuclide a which may result in the intake of one ALI of the mixture in a year;
ALI_a is the Annual Limit of Intake of radionuclide a associated with an committed effective dose equivalent of 50 mSv.

For the radionuclides present in natural uranium but excluding radon isotopes and its short-lived daughters, this becomes:

$$\frac{I\,(U\text{-}238)}{ALI(U\text{-}238)} + \frac{I\,(U\text{-}234)}{ALI(U\text{-}234)} + \frac{I\,(Pa\text{-}234m)}{ALI(pa\text{-}234m)} + \frac{I\,(Th\text{-}234)}{ALI(Th\text{-}234)} + \frac{I\,(Th\text{-}230)}{ALI(TH\text{-}230)}$$

$$+ \frac{I\,(Ra\text{-}226)}{ALI(Ra\text{-}226)} + \frac{I\,(Bi\text{-}210)}{ALI(BI\text{-}210)} + \frac{I\,(Pb\text{-}210)}{ALI(Pb\text{-}210)} + \frac{I\,(Po\text{-}210)}{ALI(Po\text{-}210)} + \frac{I\,(U\text{-}235)}{ALI(U\text{-}235)}$$

$$+ \frac{I\,(Pa\text{-}231)}{ALI(Pa\text{-}231)} + \frac{I\,(Th\text{-}227)}{ALI(Th\text{-}227)} + \frac{I\,(Ra\text{-}223)}{ALI(Ra\text{-}223)} = 1 \qquad \text{.....(2)}$$

All radionuclides for each decay chain are in secular equilibrium therefore, I (U-238) = I (U-234) = I (Th-230) = I (Ra-226) ..... = I (Po-210)
and, I (U-235) = I (Pa-231) = I (Th-227) = I (Ra-223)

The specific activity of natural uranium is 25×10^6 Bq of alpha activity/kg with:

12×10^6 Bq/kg from U-238
12×10^6 Bq/kg from U-234
8×10^5 Bq/kg from U-235

Using this information it can be shown that $I(U\text{-}235) = \frac{8 \times 4}{120 \times 5} I(U\text{-}238)$

or $= 0.05\ I(U\text{-}238)$

Therefore, ignoring the contribution due to U-235 equation (2) can be rewritten as follows with an error of less than 5%:

$$I(U\text{-}238)\left| \frac{1}{ALI(U\text{-}238)} + \frac{1}{ALI(U\text{-}234)} + \frac{1}{ALI(Th\text{-}230)} + \frac{1}{ALI(Ra\text{-}226)} + \right.$$

$$\frac{1}{ALI(Th\text{-}234)} + \frac{1}{ALI(Pa\text{-}234m)} + \frac{1}{ALI(Bi\text{-}210)} + \frac{1}{ALI(Pb\text{-}210)} +$$

$$\left. \frac{1}{ALI(Po\text{-}210)} \right| = 1 \qquad \text{.....(3)}$$

i) <u>ALI of uranium ore by inhalation</u>:

Equation (3) can be rewritten by substituting the appropriate ALIs as follows:

$$I\ (U\text{-}238)\ (5 \times 10^{-4} + 1 \times 10^{-3} + 1.7 \times 10^{-3} + 5 \times 10^{-5} + 1.7 \times 10^{-7} + 5 \times 10^{-9} + 1 \times 10^{-6} + 1 \times 10^{-4} + 5 \times 10^{-5}) = 1$$

or $I\ (U\text{-}238) = \frac{1}{3 \times 10^{-3}}$

$= 3 \times 10^{2}$ Bq

where I (U-238) is the maximum annual activity intake of U-238 in the uranium ore.

The ALI of the uranium ore is $9 \times 3 \times 10^{2}$ Bq because there are eight radionuclides at equilibrium with U-238 with individual activity of 3×10^{2} Bq.

of these $5 \times 3 \times 10^{2}$ Bq are from alpha-emitters
$4 \times 3 \times 10^{2}$ Bq are from beta-emitters.

ii) <u>ALI for uranium ore by ingestion</u>:

By inserting individual ALIs for all the radionuclides from Appendix I for the ingestion pathway in equation (3), the ALI for uraium ore by ingestion can be calculated as follows:

$5 \times 10^{-5}\ I(U\text{-}238) = 1$

$I(U\text{-}238) = 2 \times 10^{4}$ Bq

The ALI for the uranium ore is $9 \times 2 \times 10^{4}$ Bq with $5 \times 2 \times 10^{4}$ Bq from alpha-emitters and $4 \times 2 \times 10^{4}$ Bq from beta-emitters.

APPENDIX III

Annual Limit of Intake for Uranium Ore with a Th-232 to U-238 Ratio of 4:1

(1) The radionuclides considered in uranium ore are U-238, Th-234, Pa-234m, U-234, Th-230, Ra-226, Bi-210, Pb-210 and Po-210 (See Appendix II)

(2) The radionuclides considered in thorium ore are Th-232, Ra-228, Ac-228, Th-228 and Ra-224 (See Appendix II)

(3) Specific activity of U-238 = 12×10^6 Bq kg^{-1}

Specific activity of Th-232 = 4×10^6 Bq kg^{-1}

Assuming uranium ore has a Th-232 to U-238 ratio of X:1 by weight,

$$\frac{\text{activity of Th-232}}{\text{activity of U-238}} = \frac{4 \times 10^6 \text{ Bq kg}^{-1} \times X \text{ kg}}{12 \times 10^6 \text{ Bq kg}^{-1} \times 1 \text{ kg}}, \text{ therefore}$$

$$\text{activity of Th 232} = (1/3\ X) \times \text{activity of U-238}$$

For uranium ore with a ratio of thorium 232 to uranium 238 of X:1, equation (3) of Appendix II can be written as follows:

$$\frac{I(U\text{-}238)}{ALI(U\text{-}238)} + \ldots + \ldots \frac{I(Po\text{-}210)}{ALI(Po\text{-}210)} + \ldots + \frac{I(Th\text{-}232)}{ALI(Th\text{-}232)} + \ldots + \ldots \frac{I(Ra\text{-}224)}{ALI(Ra\text{-}224)} = 1$$

.....Equation (1)

where, I(U-238), I(Po-210), I(Th-232) and I(Ra-224) are the respective maximum annual activity intakes of U-238, Po-210, Th-232 and Ra-224 that may result in the intake of one ALI of ore in a year;

ALI(U-238), ALI(Po-210), ALI(Th-232) and ALI(Ra-224) are the ALIs of U-238, Th-232 and Ra-224 respectively.

APPENDIX III (CONT'D)

With the assumption that Th-232 and U-238 are in equilibrium with their respective daughter products, Equation (1) can be rewritten as:

$$I(U\text{-}238)\left|\frac{1}{ALI(U\text{-}238)}+\ldots+\frac{1}{ALI(Po\text{-}210)}\right| + 1/3\ I(U\text{-}238)X\left|\frac{1}{ALI(Th\text{-}232)}\right.$$

$$\left.\frac{1}{\ldots+\ ALI(Ra\text{-}224)}\right| = 1 \qquad \ldots\ldots\ldots \text{Equation (2)}$$

The ALIs for ingestion and inhalation of the uranium ore can then be obtained by inserting the appropriate ALIs in Equation (2).

i) For the ingestion pathway:

$$I(U\text{-}238)\ [4.5 \times 10^{-5}] + 1/3\ I(U\text{-}238)X\ [2.8 \times 10^{-5}] = 1$$

$$\text{or } I(U\text{-}238) = \frac{10^5}{4.5 + 0.93X}$$

solving for X

X	I(U-238)
1	1.8×10^4
2	1.6×10^4
3	1.4×10^4
4	1.3×10^4

Since the ratio of Th-232 to U-238 in some Elliot Lake ores is as high as 4:1, the ratio of 4:1 is chosen as the upper limit.

For uranium ore with a ratio of Th-232 to U-238 of 4:1,
$I(U\text{-}238) = 1.3 \times 10^4$ Bq and $1/3\ I(U\text{-}238) = 1.6 \times 10^4$ Bq

Therefore, the ALI in terms of all the activities of constituents in the ore is 2×10^5 Bq,

with $5 \times 1.3 \times 10^4$ Bq from alpha emitters in the U-238 claim + $3 \times 1.6 \times 10^4$ Bq from alpha emitters in the Th-232 chain

and $4 \times 1.3 \times 10^4$ Bq from beta emitters in U-238 chain + $2 \times 1.6 \times 10^4$ Bq from the beta emitters in the Th-232 chain.

APPENDIX III (CONT'D)

ii) A similar method can be used to calculate the ALI for this uranium ore for the inhalation pathway:

I(U-238) for the inhalation pathway = 8×10^1 Bq

When X = 4 (Th-232 to U-238 is 4:1),

1/3 I(U-238)X = 1×10^2 Bq.

The ALI for this uranium ore in terms of total activities of all the constituents is 1.0×10^3 Bq,

with $5 \times 8 \times 10^1$ Bq from alpha emitters in the U-238 chain plus $3 \times 1.0 \times 10^2$ Bq of alpha from Th-232 chain,

and $4 \times 8 \times 10^1$ Bq from beta emitters in the U-238 chain plus $2 \times 1.0 \times 10^2$ Bq of beta from the Th-232 chain.

APPENDIX IV

Calculation of Derived Surface Contamination Limits for Uranium Ore with a Th-232 to U-238 Ratio of 4:1

a) For the inhalation pathway:

From Table I,

the ALI of this uranium ore is 1.2×10^3 Bq and can be expressed as either

5.0×10^2 Bq of beta activity or 7.0×10^2 Bq of alpha activity

Using a resuspension factor of 2×10^{-6} m^{-1} and the volume of air intake by a worker in a year of 2.4×10^3 m^3,

the DSCL is

$$\frac{12.0 \times 10^2 \text{ Bq}}{2.4 \times 10^3 \text{ m}^3} \times \frac{1}{2 \times 10^{-6} \text{ m}^{-1}} = 2.5 \times 10^5 \text{ Bq/m}^2$$

where $\frac{5}{12} \times 2.5 \times 10^5$ Bq/m^2 is beta activity

$= 1.0 \times 10^5$ Bq/m^2

and 1.5×10^5 Bq/m^2 is alpha activity

$= 2.0 \times 10^5$ Bq/m^2

APPENDIX IV (CONT'D)

b) For the ingestion pathway:

Assuming a daily intake of contaminants from a 10^{-3} m^2 area, a 2000 working hour year and an 8 hour working day, the DSCL can be calculated by:

$$\frac{\text{ALI}}{10^{-3}\ m^2/\text{day} \times \frac{2000\ \text{h/a}}{8\ \text{h/day}}} \quad \text{Bq/a}$$

For this uranium ore, the ALI = 2.0×10^5 Bq of (beta and alpha)/a

i) The DSCL = $\frac{2 \times 10^5}{250 \times 10^{-3}}$ Bq/m^2

= 8×10^5 Bq (beta and alpha)/m^2

of which 3×10^5 Bq/m^2 is beta

5×10^5 Bq/m^2 is alpha

APPENDIX V

Derivation of the Amount of Fresh Yellow Cake on Surfaces with one DSCL

DSCL for fresh yellowcake = 3×10^5 Bq alpha activity/m^2

Specific Activity of U-238 + U-234 = 25 MBq/kg

The amount of yellowcake on $1m^2$ of the contaminated surface (assuming yellowcake contains 80% U - the upper range of uranium content in yellowcake)

$$= \frac{3 \times 10^5}{25 \times 10^6} \text{ kg} \times \frac{1}{0.8}$$

$$= 1.5 \times 10^{-2} \text{ kg}$$

= 15 grams.

This is equivalent to $\frac{15 \times 10^3 \text{ mg}}{10000 \text{ cm}^2}$

= 1.5 mg/cm^2 - which is visible against a contrasting surface.

APPENDIX VI

Derivation of the Amount of Ore on a Surface Contaminated with one DSCL of Low Grade (0.2%U) Uranium Ore

The DSCL of ore expressed in terms of alpha activities = 4×10^5 Bq/m^2 (see Table III). The activity contributed by U-238 is one fifth of this (i.e. 8×10^4 Bq/m^2) since there are five alpha emitters in the U-238 chain.

Specific Activity of U-238 = 12 MBq/kg

the amount of U-238 on of 1 m^2 of surface contaminated with 1 DSCL

$$= \frac{8 \times 10^4}{1.2 \times 10^7} \text{ kg}$$

$$= 6.8 \times 10^{-3} \text{ kg.}$$

For 0.20% ore

the amount of ore that contains 8×10^4 Bq of U-238

$$= \frac{6.8 \times 10^{-3} \times 100 \text{ kg}}{0.2}$$

$$= 3 \text{ kg.}$$

There will be approximately 3000 grams of ore on a surface of one square metre contaminated with one DSCL of ore.

- Simple housekeeping will ensure compliance as well as recovery of valuable resources.

APPENDIX VII

Derived Surface Contamination Limit For Release of Slightly Contaminated Materials For Use Outside the Nuclear Industry

A) Considering external irradiation of the skin:

Various assumptions can be made as to what a member of the public would do with slightly contaminated materials and equipment. The author has chosen to assumed that the worst case would be a person sleeping on such contaminated surfaces.

Assuming a person sleeps 8 hours per day, in a year he would spend 365 x 8 hours in close contact with the contaminated surfaces. With a dose rate to the basal cell layer of 0.2 nGy/h per Bq/m^2 of beta activity and a surface contamination limit of 10^4 Bq/m^2 (see text section E), the annual dose to the person would be:

$$0.2 \times 10^{-6} \times 10^4 \times 365 \times 8$$

$$= 5.8 \text{ mSv.}$$

This is about 12% of the 50 mSv dose limit for the skin for members of the public.

B) Considering exposure to radon daughters:

1) Assuming a room with dimensions of 2.5m x 4.5m x 4.5m is completely lined with contaminated material, the area of contamination is therefore:
$2 \times (4.5 \times 4.5) + 4\ (2.5 \times 4.5)\ m^2$
$= 86\ m^2$

Room volume = $2.5 \times 4.5 \times 4.5 = 51\ m^3$

2) Assuming contamination level = 1×10^4 Bq/m^2 (Section E of text)

3) Assuming 25% of the total alpha activity in the surface contaminant is from radium-226. (For most uranium process products or wastes, ratios of activities of Ra-226 to other alpha emitters range from 1:4 for tailings to 1:5 for uranium concentrates.)

4) The total amount of Ra-226 on the room surfaces is
1×10^4 Bq/m^2 x 86 m^2 x 25%
$= 2.2 \times 10^5$ Bq

5) The rate of generation of radon-222 is 2.1×10^{-6} Bq/s per Bq of Ra-226.

6) Assuming radon emanation fraction of 20%. (A typical value for emanation of radon gas from porous media*. The emanation rate from porous material is used in order to give a conservatively high value, however, as mentioned in the text (Secton E) the uncontrolled use of contaminated porous materials would not be permitted.)

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* M.C. O'Riordan, A.C. James and K. Brown, "Some Aspects of Human Exposure to Ra-222 Decay Products", Radiation Protection Dosimetry 3: 75-82 (1982).

APPENDIX VII (CONT'D)

The emanation rate of Rn-222 would be

$$\frac{2.1 \times 10^{-6} \text{ Bq/s} \times 2.2 \times 10^{5} \text{ Bq Ra-226} \times 20\%}{1 \text{ Bq Ra-226}}$$

$$= 0.09 \text{ Bq/s}.$$

7) Assuming one air change per hour, the concentration of radon-222 in the room would be:

$$\frac{0.09 \text{ Bq/s}}{50 \text{ m}^3 \times 1.0/\text{hr}}$$

$$= \frac{0.09 \text{ Bq} \times 3600}{50 \text{ m}^3 \times 1.0}$$

$$= 6.5 \text{ Bq/m}^3$$

$$\text{or} = 6.5 \times 10^{-3} \text{ Bq/L}$$

Since at 1 air change/hour the concentration of radon daughters is 0.53 WL per 100 pCi/L (see attached) (i.e. 0.53 WL per 3.7 Bq/L) of radon 222,

the concentration of radon daughters in the room will be

$$\frac{0.53 \text{ WL} \times 6.5 \times 10^{-3} \text{ Bq/L}}{3.7 \text{ Bq/L}}$$

$$= 9.3 \times 10^{-4} \text{ WL}$$

$$= 9.3 \times 10^{-4} \text{ WL} \times 2.08 \times 10^{-5} \text{ J/m}^3/\text{WL}$$

$$= 1.90 \times 10^{-8} \text{ J/m}^3.$$

According to ICRP-23, a person spends about 19 hours per day indoors with a breathing rate of about 14.3m^3 per day or 5220m^3 per year.

Hence the annual intake of radon daughters will be

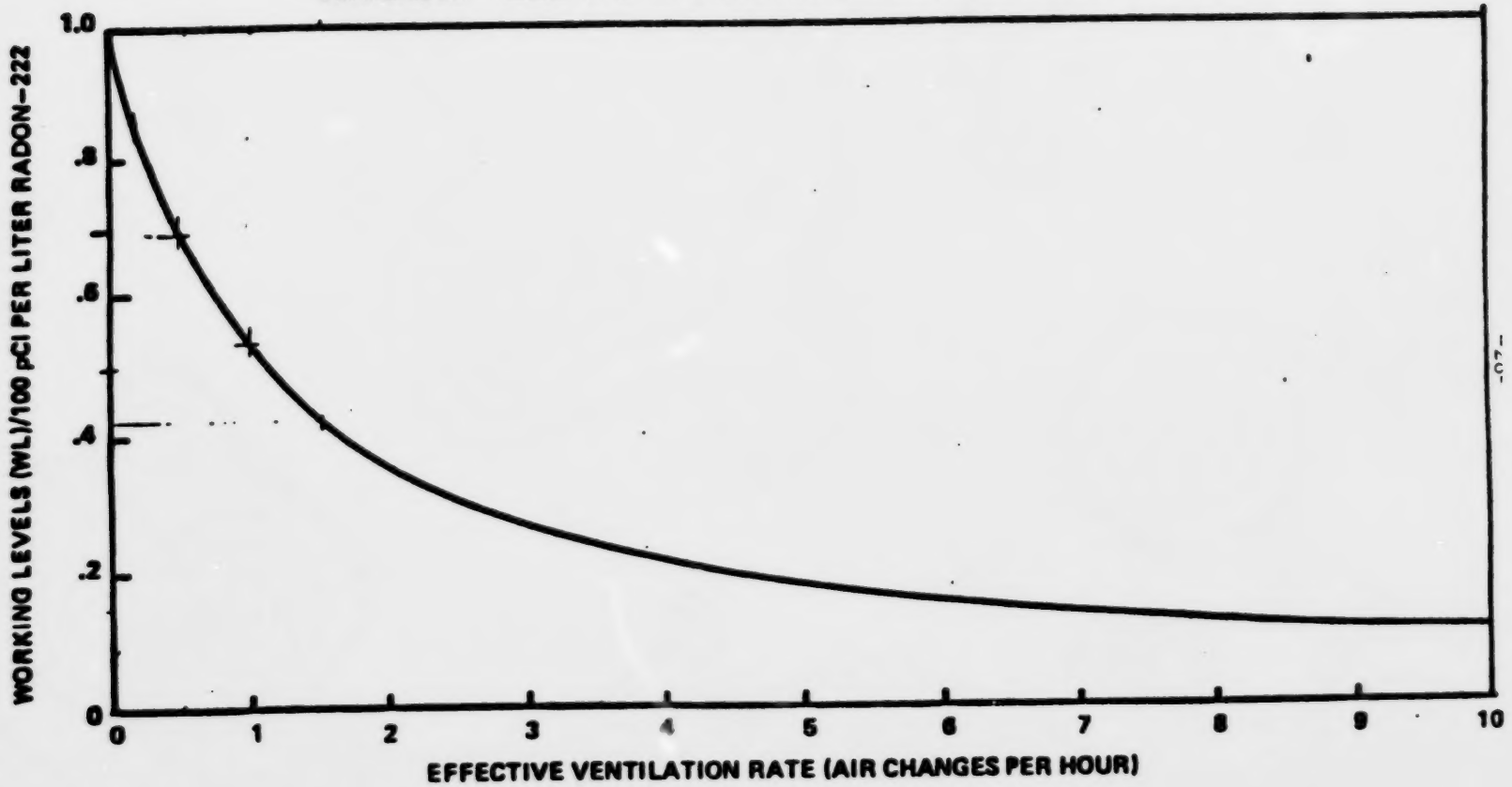
$$1.90 \times 10^{-8} \text{ J/m}^3 \times 5220\text{m}^3 = 1.0 \times 10^{-4} \text{ J}.$$

This is about 0.5% of the annual occupational limit on intake for radon daughters (0.02 J) recommended by ICRP-32. Assuming that the effective dose equivalent per unit intake of radon daughters is the same for the public as for workers, then, this represents an intake corresponding to 5% of the annual limit on effective dose equivalent for members of the public.

0.5 1.5

0.1 ~0.42

FIGURE A—2
WORKING LEVELS (WL) PER 100 pCi PER LITER OF RADON—222 VS EFFECTIVE VENTILATION RATE



Source: "A Preliminary Evaluation of the Control of Indoor Radon Daughter Levels in New Structure". The United States Environmental Protection Agency, EPA-520/4-76-018, November, 1976.